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Composite Fan Blade Design for Advanced Engine Concepts

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Abstract

The aerodynamic and structural viability of composite fan blades of the revolutionary Exo-Skeletal (ref. 1) engine are assessed for an advanced subsonic mission using the NASA EST/BEST (ref. 2) computational simulation system. The Exo-Skeletal Engine (ESE) calls for the elimination of the shafts and disks completely from the engine center and the attachment of the rotor blades in spanwise compression to a rotating casing. The fan rotor overall adiabatic efficiency obtained from aerodynamic analysis is estimated at 91.6 percent. The flow is supersonic near the blade leading edge but quickly transitions into a subsonic flow without any turbulent boundary layer separation on the blade. The structural evaluation of the composite fan blade indicates that the blade would buckle at a rotor speed that is 3.5 times the design speed of 2000 rpm. The progressive damage analysis of the composite fan blade shows that ply damage is initiated at a speed of 4,870 rpm while blade fracture takes place at 7,640 rpm. This paper describes and discusses the results for the composite blade that are obtained from aerodynamic, displacement, stress, buckling, modal and progressive damage analyses. It will be demonstrated that a computational simulation capability is readily available to evaluate new and revolutionary technology such as the ESE.

Introduction

For many decades, researchers have steadily worked on improving the performance of gas turbine engines. Major advances were made in the areas of materials, structures, controls, reliability, thermal cycles, thrust to weight ratio, and overall pressure ratios. Improving performance, reducing operating cost, lowering emission and noise, and enhancing structural reliability of gas turbine engines are prudent to meet the challenges of the new century. Recent research efforts at NASA Glenn Research Center lead to the development of an advanced and revolutionary engine concept, Exo-Skeletal (ref. 1) engine, to meet the increasingly more demanding and challenging requirements for next generation jet engines. The ability to produce lighter engines than conventional engines with higher efficiency and improved reliability compared to present technology is essential. The revolutionary ESE concept meets the aforementioned challenges because it eliminates the shafts and disks completely from the engine center while attaching the blades in spanwise compression to a rotating casing (drum rotor).

The projected benefits of the ESE include: (1) light weight due to a reduction in the number of parts and elimination of shafts and disks, (2) improved fatigue life due to operation of rotor blades in compression stress fields, (3) minimization or elimination of the foreign object damage effect and the unbalance resulting therefrom, (4) higher rotor efficiency over conventional rotors due to the elimination of blade tip losses, (5) higher mass flow rate, (6) decrease in sealing requirements, and (7) possible application to various engine regimes including subsonic, supersonic and hypersonic. Adequate aerodynamic and structural performances are critical to the workability of the ESE. Figure 1 shows a

projected view of a typical ESE drum rotor. As illustrated in that figure, the blades are placed in spanwise compression and attached to a drum rotor. The blades will be supported by a stress tuner ring at the inner diameter in order to avoid flutter and buckling. A race shell bearing case is used to support the rotating casing. The bearings will transfer the loads between the drum rotor and the static backbone shell and permit relatively free rotation with minimum friction. A finite element model of a hypothetical assembled ESE is depicted in Figure 2. Note the open channel in the center of the engine due to the elimination of the center shaft and disk. The objective of this paper is to describe and demonstrate the aerodynamic and structural viability of Exo-Skeletal fan blades in an advanced subsonic mission.

Description of Computational Simulation Used in Aero/Structural Design of Exo-Skeletal Blades

The NASA in-house computer code EST/BEST (ref. 2) (Engine Structures Technology Benefit Estimator) is used to evaluate the aerodynamic and structural performance of the Exo-Skeletal fan blades. EST/BEST is a multi-scale, multi-level, and multi-disciplinary analysis computer code developed to assess the performance of engine structures. As shown in figure 3, the disciplines “Virtual Concurrent Engineering” that are integrated in EST/BEST include the following: engine component analysis modelers, multi-factor models for material behavior, multi-scale composite mechanics, structural analysis of metallic and composite components, progressive structural fracture for evaluating durability and integrity, thermo-mechanical and acoustic fatigue, emission requirements, hot fluid mechanics, heat-transfer, and probabilistic simulations. The modules used to obtain the results that are presented in this paper are: (1) CSPAN (ref. 3) for spanline analysis to determine the component’s flow path, initial velocity diagrams, hub radii, and initial blading geometry; (2) Blade (ref. 4) design code to design a blade shape, calculate flow losses and adiabatic efficiency; (3) Flow (ref. 5) code to assess the aerodynamic performance of the designed blade shape and calculates the blade surface pressures and temperatures; (4) Composite modelers (ref. 6); (5) Finite element modelers (ref. 7); (6) Finite element analysis (ref. 8); and (7) Progressive damage (ref. 9) evaluation of composite structures.

Aerodynamic design and structural evaluation of an Exo-Skeletal fan rotor blade for an advanced subsonic mission are carried out to demonstrate that blades can be placed in compression while maintaining, if not enhancing, its aerodynamic and structural performance. The aerodynamic design will include a discussion of the aerodynamic flow solution, aerodynamic loading and pressure ratio across the blade span. The structural evaluation of the composite fan blade will comprise displacement, stress, frequency, buckling, and progressive damage evaluation to assess the blade damage and fracture rotor speed.

Aerodynamic Design of Exo-Skeletal Blades

The fan rotor considered here consists of a single stage with 28 blades and is designed for a pressure ratio of 1.50. The aerodynamic analysis performed by the computational simulation predicted the rotor’s overall efficiency to be about 91.6 percent. If the blade was to be made of advanced material like graphite epoxy composite, it would weigh about 5.6 kg. This weight is only about 20 percent of a conventional engine fan blade. The blade rotor speed is 2000 rpm at cruise with a tip speed of 366 m/sec with a corrected inlet flow rate of 1270 kg/sec. The geometry of the airfoil for the fan rotor blade is presented in figure 4 for three sections: hub, mean and tip. In ESE configuration, unlike conventional engine design, the blade hub is attached to the drum-rotor. The hub section maintains the largest thickness to chord ratio while the tip (inner) section remains the thinner section of the blade. For the particular Exo-Skeletal design presented in this paper, the hub maximum thickness to chord ratio is 5.5 percent while the tip maximum thickness to chord ratio is 3.5 percent. Note that the Exo-Skeletal hub maximum thickness is

less than that of the hub of conventional engines, which could reach 9 percent. The Exo-Skeletal hub thickness need not be as large as the one used in conventional engines. This reasoning is justified by the fact that large airfoil thickness in the outer section can cause choking or strong shocks and the use of composites enable the reduction in the maximum thickness.

In figure 5, the surface isentropic Mach number is the chord nondimensional blade element coordinate for two sections: near the hub (outer) and mean. The flow analysis indicates that the flow is supersonic near the blade leading edge but quickly transitioned into subsonic flow without any turbulent boundary layer separation on the blade. As illustrated in the same figure, the surface isentropic Mach number levels off and declines to subsonic level as it approaches the trailing edge. In addition to Mach number plots, the ratio of the surface static pressure over the inlet total pressure is plotted in figure 6 for near hub and mean sections against the chord nondimensional blade element coordinate. The surface Mach number and pressure ratio are plotted for both suction and pressure surfaces. Based on the results presented in figures 5 and 6, it is obvious that the blade aerodynamic design is very appropriate for use in ESE applications. Furthermore, the work done by the blade chord is sufficient to produce the required pressure rise. The spike in the pressure at the leading edge is resulting from a mild leading edge oblique shock.

Figure 7 shows the diffusion factor or what is known as the aerodynamic loading and the blade pressure ratio as a function of the blade radius percent from the hub. A diffusion factor of less than 0.6 indicates that no flow separation has taken place. With the current design, the maximum value of the diffusion factor is about 0.52 at a blade radius that is 70 percent away from the hub. The pressure ratio is about 1.58 at the blade hub and decreases to 1.38 at the blade tip (inner most section). Next, the blade structural model is discussed and results from the structural evaluation are presented.

Exo-Skeletal Composite Fan Blade Modeling and Structural Evaluation

Once the blade airfoil design is complete and satisfactory performance is obtained, the various airfoil sections can be used to generate the blade finite element model. The flow analysis provided detailed surface pressure and temperature distribution, which will be used to load the blade along with the rotor speed. The fan rotor composite blade finite element model is shown in figure 8. The model consists of 40 shell elements with 55 nodes at 6 degrees of freedom per node. Note that the boundary conditions for the composite blade are as follows: (1) all displacements and rotations are fixed in the hub (outer section) and (2) displacements in y and z directions (chordwise and flapwise) are fixed at tip (inner section). Note that the boundary conditions of the blade remain unchanged for the stress, displacement, frequency, buckling and damage progression analyses. The composite blade is made of graphite epoxy with a fiber volume ratio of 55 percent and a void volume ratio of 2 percent. The ply layup orientation is $[30,-30,0,0,30,0]_s$ with a ply thickness of 0.0127 cm. The selected composite system has a cure temperature of 188 °C and an overall density of 1.5 g/cm (ref. 3).

The results from the stress analysis at design speed of 2000 rpm and design pressure ratio of 1.5 are summarized in table 1. The maximum tensile and compressive longitudinal, transverse, and shear pressure and suction surfaces ply stresses are tabulated. In addition to ply stresses, the ply strength in the longitudinal, transverse, and shear directions are also listed in the same table. If one is to compute the margin of safety defined as: safety factor -1, would find the largest margin of safety (15.7) in the ply longitudinal tensile stress and the smallest margin of safety (1.05) in the compressive shear stress. That means that an increase of the ply shear stress of 105 percent would cause failure. The type of information presented here is important because it helps in assessing the safety of the structure at design conditions. Note that the location of maximum stress is located near the hub-drum rotor attachment region. In addition, to stress analysis, displacement analysis is performed on the composite blade at design conditions. Figure 9 shows the overall resultant displacements. At design speed, the maximum displacement is about one

centimeter and it occurs on the leading edge of the blade mid span region. The maximum spanwise displacement in the direction of the engine center is about one tenth of one centimeter. The spanwise displacement is important to estimate because it could be used as “control” type data to limit the growth of the stress tuner.

The Exo-Skeletal fan blade first five natural frequencies at three distinct operating speed are presented in table 2. At a rotor speed of 1500 rpm, the blade first natural frequency is estimated at 220 cps while the fifth natural frequency is about 572 cps. As the speed increases to 2000 rpm, the frequency drops about 3 percent. As the speed is increased from 2000 to 2500 rpm, the frequency is reduced an additional 4 percent. The drop on the frequency is consistent with the physical boundary conditions of the blade. When blades are held in compression, it is expected to detect a drop in frequency. It is important to notice that at various rotor speeds the blade frequencies do not change sporadically but change in a structured pattern. The information obtained here can be of great use to test engineers as it allows the knowledge of what operating frequencies to avoid as the rotor speed increases. In the case of conventional blade design, the frequency increases with the speed due to increase in centrifugal stiffening and due to the fact that conventional blades operate in tensile stress fields.

In addition to frequency analysis, buckling analysis is performed to predict the buckling rotor speed of the Exo-Skeletal blade. The results obtained from the buckling analysis are presented in figure 10. The fan blade would buckle at speed of 6800 rpm. That is about 3.5 times the design rotor speed. The buckling mode shape indicates that the buckling of the blade is similar to that of a column under compressive load. The buckling analysis is a further indication that the blade design is very adequate for use in Exo-Skeletal engine configuration.

The stress analysis presented earlier indicated that at design rotor speed and pressure ratio, no ply failure had taken place. For operational safety, a reliable evaluation of damage and fracture rotor speeds must be carried out. In EST/BEST, progressive damage and fracture analysis composite structures are performed using a dedicated computational simulation computer code named CODSTRAN (ref. 9). The CODSTRAN computer code is made up of the following modules: (1) composite mechanics ICAN (ref. 6), (2) finite element analysis MHOST (ref. 8), and (3) damage propagation tracking. The evaluation of structural durability is done in the damage propagation module in CODSTRAN. The composite mechanics module is called before and after each finite element analysis. The composite mechanics module computes the composite ply properties at each node of the finite element model. Computation is based on fiber and matrix constituents and properties, and the composite lay-up. Individual ply failure modes are assessed by ICAN using failure criteria that account for broken fiber, micro-buckling, crushing and delamination of fiber, and matrix cracking. These failure modes are associated with the negative and positive limits of the six-ply stress components in the material directions 1 to 3, combined stress failure criterion that takes into account combined stresses, and the relative rotation criterion that checks for interply delamination. Note that in the damage analysis, it is assumed that design surface pressures that are obtained from the flow analysis are continuously acting on the blade surface. The rotor speed is the loading that is incremented until the blade is damaged and fractured.

The progressive damage evaluation of the Exo-Skeletal composite fan blade indicates that the initial damage occurs due to three failure modes: (1) longitudinal compressive, (2) combined stress, and (3) relative rotation criterion. Figure 11 shows the location of the initial damage, which is near the blade leading edge and close to the hub attachment. The initial blade damage is detected at 4870 rpm, which is 2.4 times the 2000 rpm design speed. When the damage is initiated, the damage volume is found to be about 0.1 percent. The blade fracture takes place at a rotor speed of 7640, which is 3.8 times the design speed. The results also indicate that the blade would tolerate an increase of 2770 rpm in the speed beyond the speed that produced the initial damage. The assessment of the damage tolerance is important because it determines how usable the blade is after the initiation of damage. A plot of the total damage energy release rate and damage volume (percent) against the rotor speed is presented in figure 12. During the load incrementation process, significant damage can occur with small increase in speed. That is indicated in the drop in the damage energy release rate. As shown in figure 12, at the fracture speed of 7640 rpm, about 50 percent of the blade plies have been damaged.

Conclusions

The ESE concept is revolutionary. Aerodynamic design and structural evaluation of the composite fan blade for an advanced subsonic mission were presented and discussed. It was demonstrated that a readily available computational simulation could be used to assess new and advanced engine structures technology. The sound aerodynamic and structural performance of the fan rotor blades of the ESE demonstrates the viability of that engine concept. Some specific conclusions are listed here: (1) Exo-Skeletal fan blades can be aerodynamically designed to operate with high efficiency, (2) Exo-Skeletal composite fan blades possess excellent buckling resistance; and (3) Exo-Skeletal composite fan blades can be designed to sustain significant damage before fracture. It was also shown that the use of established micro-mechanics, progressive fracture and finite element modules is sufficient to estimate the damage and fracture rotor speed of composite rotor blades.

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**Table 1. Exo-Skeletal Fan Composite Rotor Blade Pressure Surface,
and Suction Surface Ply Stresses, and Ply Strengths**
(Obtained at Design Conditions: 2000 rpm Rotor Speed and 1.5 Pressure Ratio)

Pressure Surface Ply Stresses (MPa)					
Maximum Tensile			Maximum Compressive		
Longitudinal	Transverse	Shear	Longitudinal	Transverse	Shear
89	29	2	301	23	27
Suction Surface Ply Stresses (MPa)					
Maximum Tensile			Maximum Compressive		
Longitudinal	Transverse	Shear	Longitudinal	Transverse	Shear
88	29	4	237	23	24
Ply Strengths (MPa)					
Tensile		Compressive		Shear	Shear
Longitudinal	Transverse	Longitudinal	Transverse	(12)	(23)
1487	68	758	157	57	49

**Table 2. Exo-Skeletal Fan Composite Blade First Five Frequency at
Three Operating Rotor Speed (Design Speed = 2000 rpm)**

	Speed (1500 rpm)	Speed (2000 rpm)	Speed (2500 rpm)
Frequency 1 (cps)	220	214	206
Frequency 2 (cps)	310	303	294
Frequency 3 (cps)	353	345	335
Frequency 4 (cps)	526	520	512
Frequency 5 (cps)	572	568	562

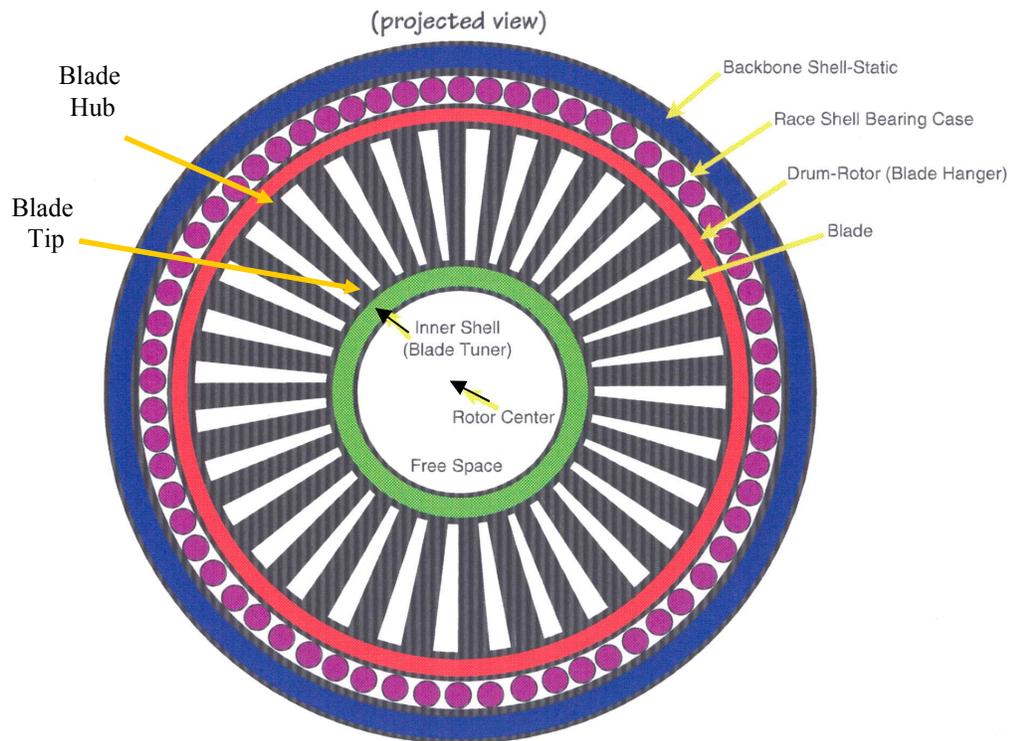


Figure 1. Exo-Skeletal Engine All Composite Drum Rotor Section

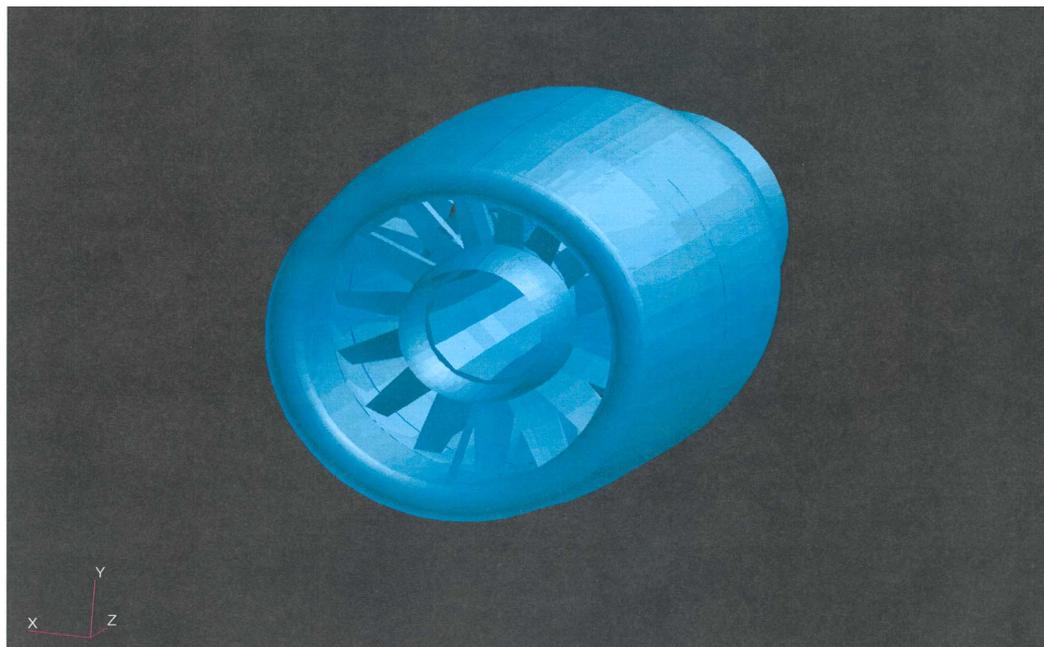


Figure 2. Finite Element Model of the Assembled Exo-Skeletal Engine

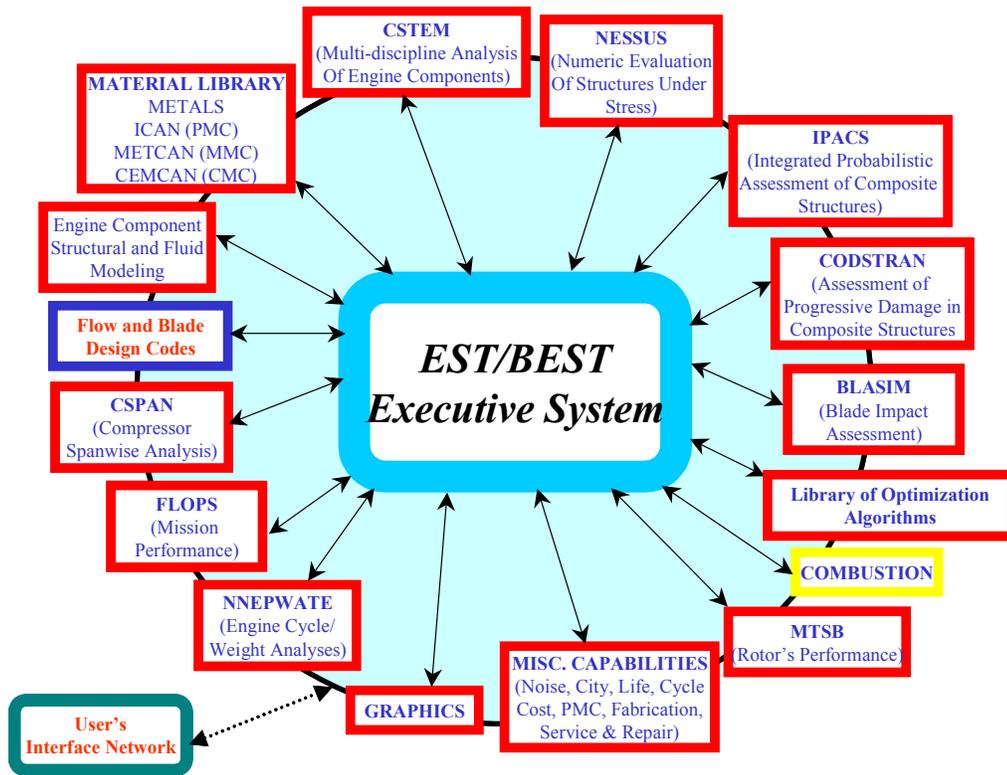


Figure 3. Engine Structures Technology Benefit (EST/BEST) Modular Chart

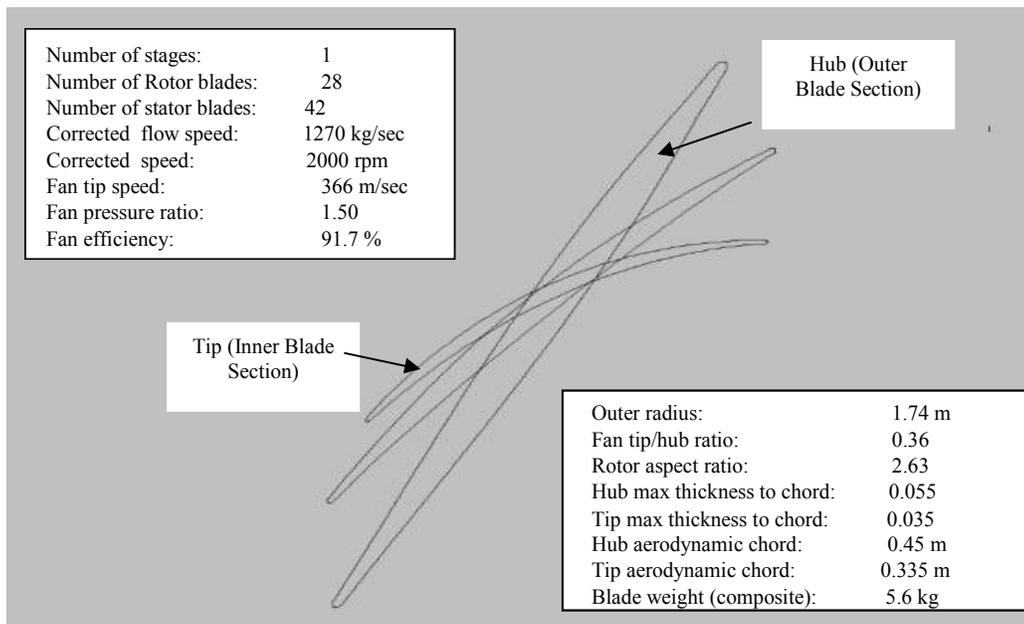


Figure 4. Exo-Skeletal Fan Rotor Geometry for Advanced Subsonic Mission

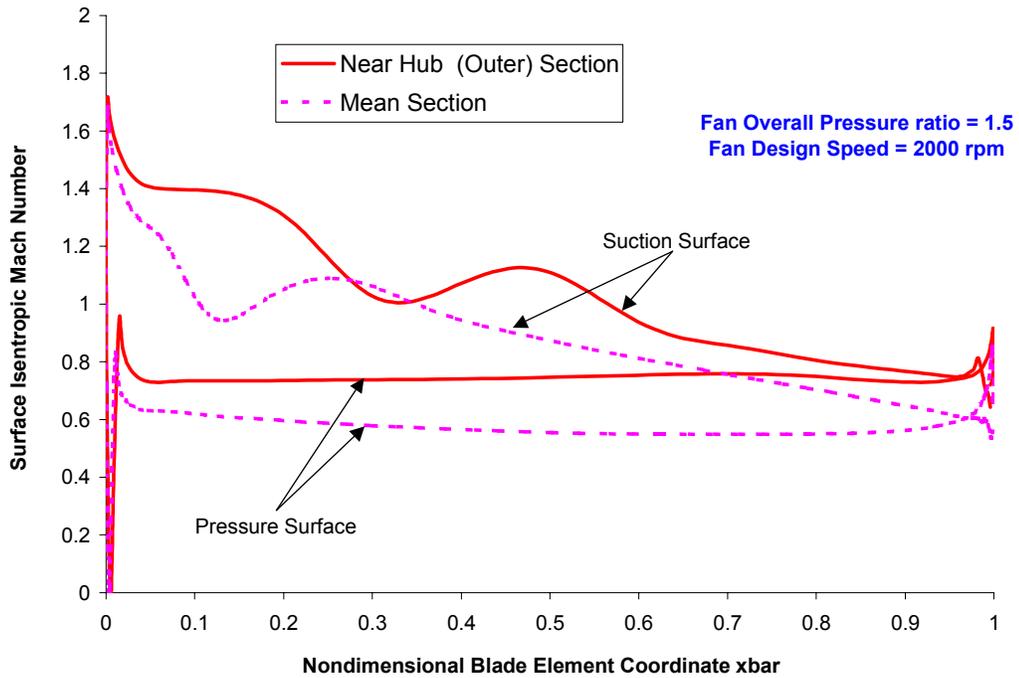


Figure 5. Rotor Surface Mach Number Plot for Fan of Exo-Skeletal Engine

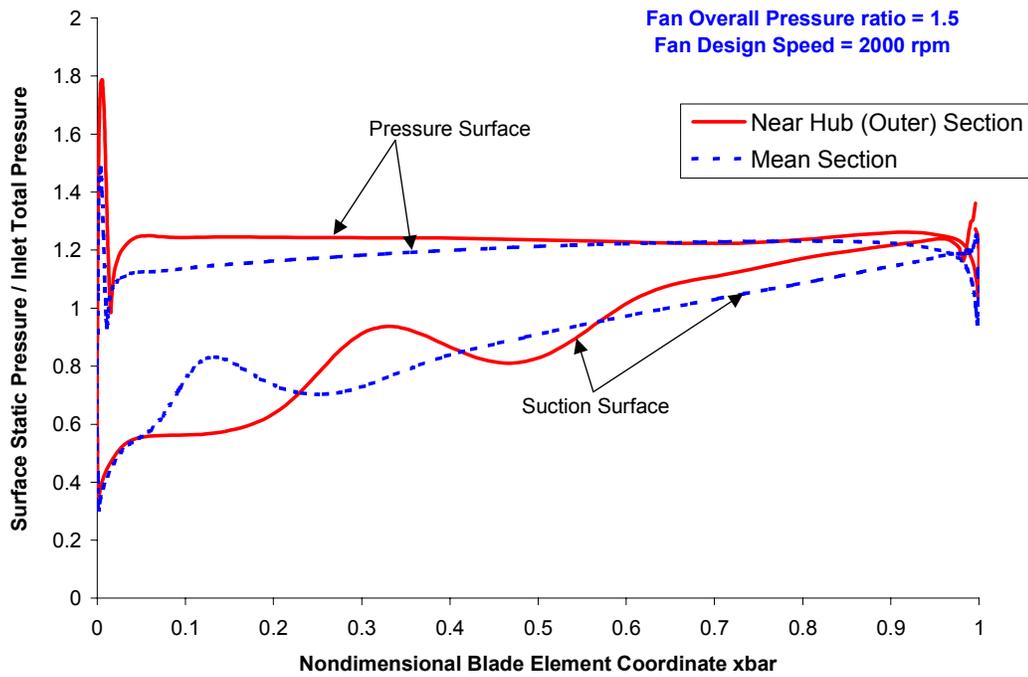


Figure 6. Rotor Surface Pressure Plot for Fan of Exo-Skeletal Engine

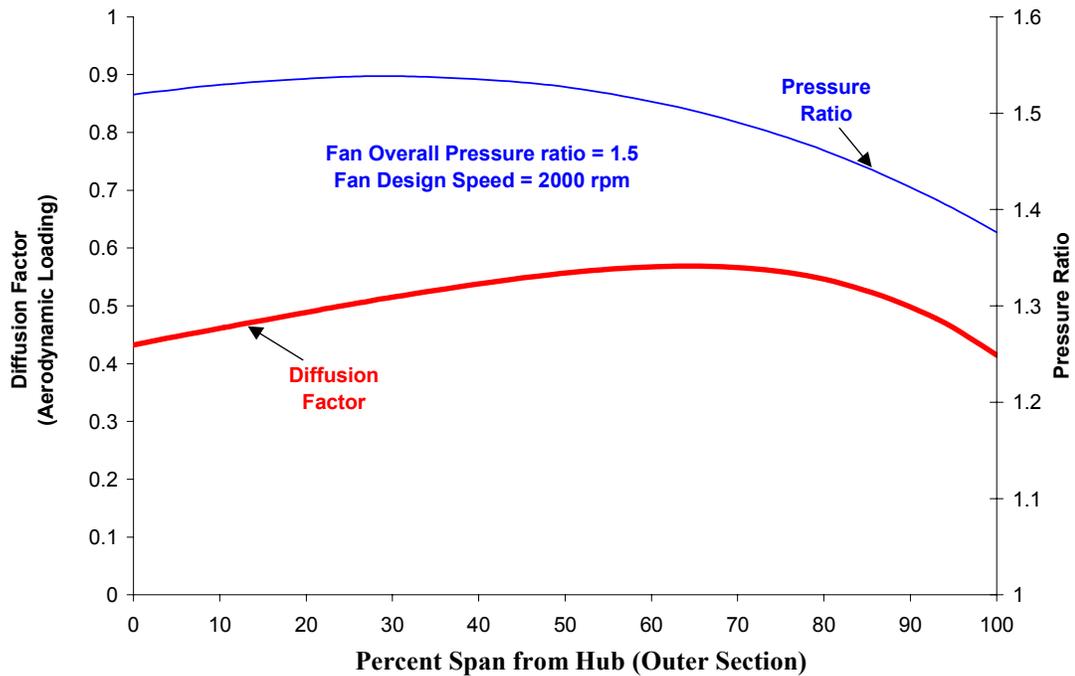
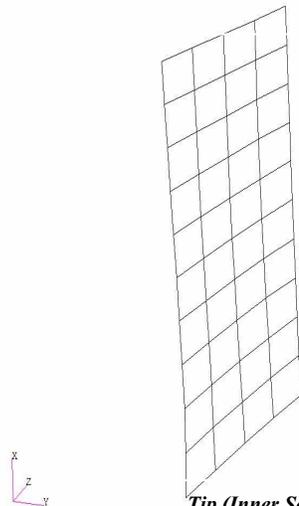


Figure 7. Rotor Aerodynamic Loading and Pressure Ratio as a Function of Blade Radius for Fan of Exo-Skeletal Engine

Hub (Outer Section) Boundary Conditions

Displacement x, y and z are fixed
 Rotation x, y and z are fixed



Material Configuration

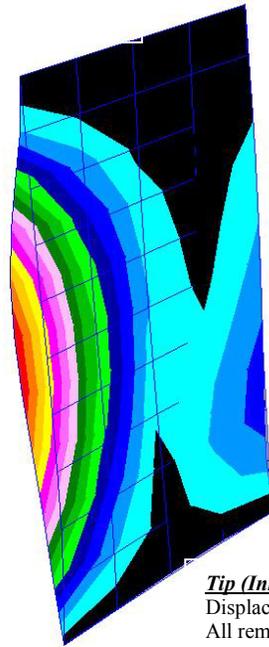
Composite: Graphite Epoxy
 Fiber Volume Ratio: 0.55
 Void Volume Ratio: 0.02
 Lay-up: [30,-30,0,0,30,0]s
 Ply Thickness: 0.0127 cm
 Cure Temperature: 188 °C
 Density: 1.50 g/cm³
 Blade Weight: 5.6 kg
 Number of Blades: 28

Tip (Inner Section) Boundary Conditions

Displacement y and z are fixed
 All remaining d.o.f are free

Figure 8. Rotor Composite Blade Finite Element Plot for Fan of Exo-Skeletal Engine (Advanced Subsonic Mission)

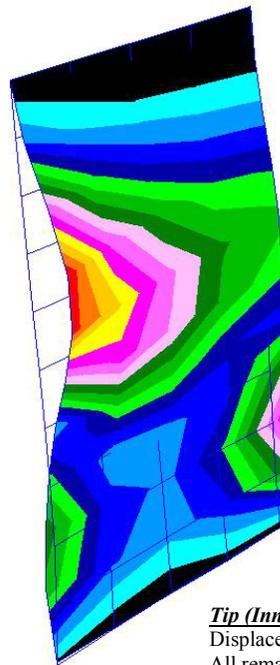
Hub (Outer Section) Boundary Conditions
 Displacement x,y and z are fixed
 Rotation x,y and z are fixed



Tip (Inner Section) Boundary Conditions
 Displacement y and z are fixed
 All remaining d.o.f are free

Figure 9. Resultant Displacements of Rotor Composite Blade (in centimeters) for Fan of Exo-Skeletal Engine (at Design Speed and Pressure)

Hub (Outer Section) Boundary Conditions
 Displacement x,y and z are fixed
 Rotation x,y and z are fixed



Buckling Speed: 6800 rpm,
 Design Speed: 2000 rpm

Tip (Inner Section) Boundary Conditions
 Displacement y and z are fixed
 All remaining d.o.f are free

Figure 10. First Buckling Mode Shape of Rotor Composite Blade for Fan of Exo-Skeletal Engine

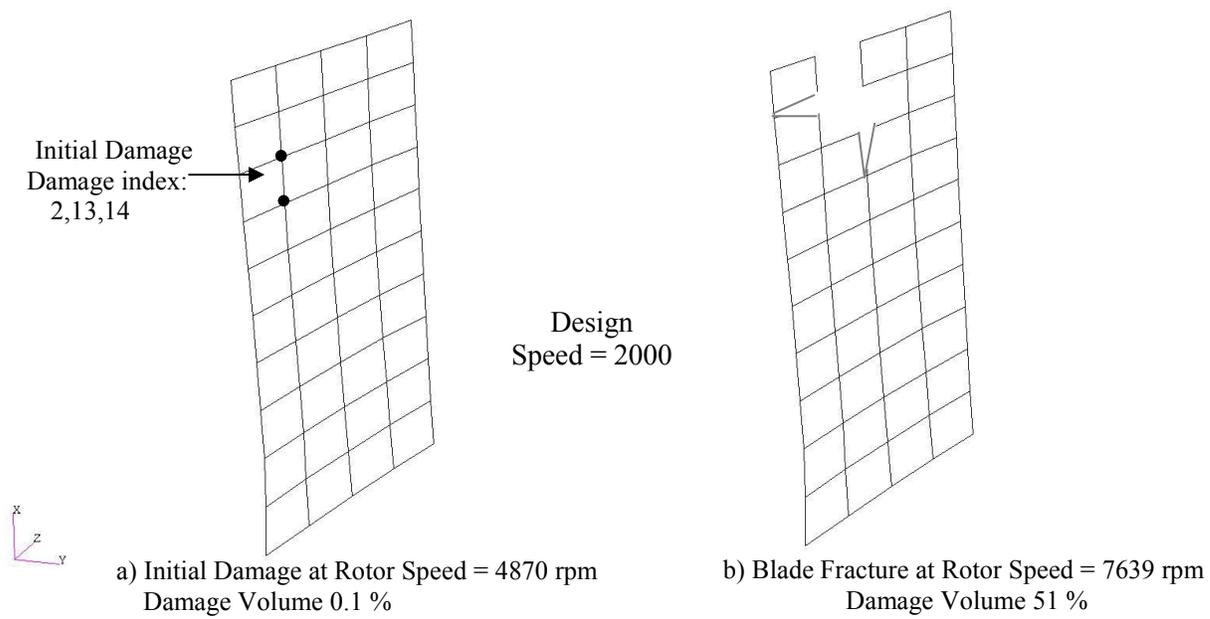


Figure 11. Damage Progression Evaluation of Rotor Composite Blade for Fan of Exo-Skeletal Engine

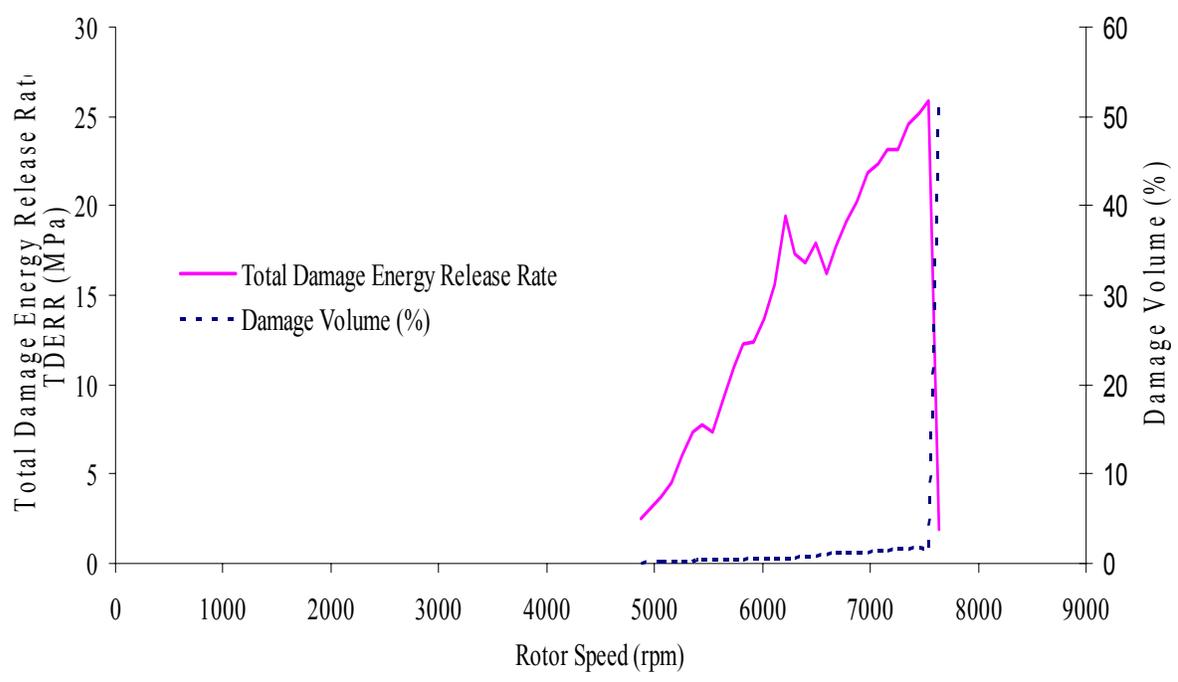


Figure 12. Total damage energy Release Rate and Damage Volume (%) with Rotor Speed for Composite Blade of Fan of Exo-Skeletal Engine

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